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(54) Title: PASSBAND FLATTENING IN AN ARRAYED WAVEGUIDE GRATING

(57) Abstract: An array waveguide grating (AWG) device in which at least one additional waveguide is provided for each input waveguide of the AWG. The or each additional waveguide is optically coupled to the first free space coupler and disposed adjacent to the respective input waveguide. In some described embodiments, one or two such additional waveguides are provided adjacent to each input waveguide and have a tapered shape designed to transform adiabatically the a single peak field in the input waveguide to a multiple peak field which produces a flattened passband at the AWG channel outputs. The additional waveguides can alternatively be provided at the output side of the AWG. Also claimed is an optical power splitter based on the same adiabatic mode shaping structure.

PASSBAND FLATTENING IN AN ARRAYED WAVEGUIDE GRATING

FIELD OF THE INVENTION

The present invention relates to arrayed waveguide gratings (AWGs), and in particular to passband flattening in AWGs. More specifically, the invention concerns an improved technique for achieving passband flattening.

BACKGROUND ART

AWGs are now well-known components in the optical communications network industry. An AWG is a planar structure comprising a number of array waveguides which together act like a diffraction grating in a spectrometer. AWGs can be used as multiplexers and as demultiplexers, and a single AWG design can commonly be used both as a multiplexer and demultiplexer. The construction and operation of such AWGs is well known in the art. See for example, "PHASAR-based WDM-Devices: Principles, Design and Applications", M K Smit, IEEE Journal of Selected Topics in Quantum Electronics Vol.2, No.2, June 1996, US 5,002, 350 and WO97/23969.

A typical AWG mux/demux 1 is illustrated in Fig.1 and comprises a substrate or "die" 1 having provided thereon at least one single mode input waveguide 2 for a multiplexed input signal, two free space couplers 3,4 (in the form of slab or star couplers) connected to either end of an arrayed waveguide grating 5 consisting of an array of transmission waveguides 8, only some of which are shown, and a plurality of single mode output waveguides 10 (only some shown) for outputting respective wavelength channel outputs from the second (output) slab coupler 4 to the edge 12 of the die 1. In generally known manner, there is a constant predetermined optical path length difference between the lengths of adjacent waveguides 8 in the array which determines the position of the different wavelength output channels on the output face of the second slab coupler 4. Typically, the physical length of the waveguides increases incrementally by the same amount, ΔL, from one waveguide to the next, where

$\Delta L = m\lambda_c/n_c$

where λ_c is the central wavelength of the grating, n_c is the effective refractive index of the array waveguides, and m is an integer number. In known manner, the waveguides and slab

couplers typically are formed as "cores" on a silicon substrate (an oxide layer is commonly provided on the substrate prior to depositing the waveguide materials) and are covered in a cladding material, this being done for example by Flame Hydrolysis Deposition (FHD) or Chemical Vapour Deposition (CVD) fabrication processes.

In the described AWGs, the passband (i.e. shape of the transmission spectrum $T(\lambda)$, which is a plot of dB Loss against Wavelength) for each output channel generally corresponds to the coupling of a Gaussian beam into a Gaussian waveguide, and is therefore itself Gaussian-shaped. In many situations it would be more desirable for the AWG to have a flat passband. This is generally because a Gaussian passband requires accurate control over emitted wavelengths, thus making it difficult to use in a system. Various ways of achieving a flat passband have been proposed, one way being to use "near field shaping". This involves creating a double-peaked mode field from the (single peak) input mode field. When this double-peaked field is convoluted with the single mode output waveguide, the resulting passband takes the form of a single, generally flat peak.

One way of creating the necessary double-peaked field is to use an MMI (Multi-Mode Interferometer) on the end of the input waveguide, adjacent the first slab coupler, as shown in Fig.2(a). The MMI creates higher order modes from the single mode input signal and these multiple modes give rise to a double-peaked field at the output of the MMI. US5,629,992(Amersfoort) describes this passband flattening technique in detail.

An alternative technique is to use a parabolic-shaped taper or "horn" on the end of the input waveguide, as shown in Fig.2(b). This is described in JP 9297228A. The parabolic taper gives rise to continuous and rapid mode expansion of the fundamental mode of the input signal along the length of the taper, which causes excitation of the second order mode, the presence of the two modes thus forming a double-peaked field at the output end of the taper.

However, both the above-described techniques suffer from the disadvantage that the passband-flattening feature (namely the MMI or parabolic horn) create significant insertion loss in the device. This is largely due to losses through radiation modes which are

generated at discontinuities in the input waveguide, for example at the input edge of the MMI. Also, the parabolic horn has its steepest taper angle in the narrowest part of the taper (the beginning), which can encourage radiation losses. Such passband flattening features are also significantly wavelength dependent, which is undesirable. Moreover, the presence of higher order (guided) modes can lead to chromatic dispersion problems if all the modes, in particular the fundamental and second order modes, are not in phase with one another where they enter the first slab coupler, from the output of the MMI or parabolic horn.

An alternative proposed solution which does not rely on mode conversion is to use Y-branch couplers or power splitters on the ends of the input waveguides, as described in US 5,412,744 (see Fig.2(c)) and US5,706,377. However, there are significant fabrication difficulties with such structures since they require the fabrication of a very thin blunt (generally rectangular shaped slot) between neighbouring input waveguides to ensure that the structure is adiabatic i.e. that no mode conversion occurs. This means the device is highly sensitive to fabrication errors.

US 5,978,532 discloses a split single mode waveguide structure formed in the end of the input or output waveguide and coupled to the first or second slab coupler respectively, for forming a double-peaked field. However, such a structure may be difficult to fabricate, requiring etching of a fabricated waveguide. Moreover, it may suffer from the same disadvantage as the Y-branch structures mentioned above, in that it incorporates a very thin blunt or sharp point.

It is an aim of the present invention to avoid or minimize one or more of the foregoing disadvantages.

SUMMARY OF THE INVENTION

According to a first aspect of the invention there is provided an arrayed waveguide grating (AWG) device comprising:

at least one input waveguide optically coupled to a first free space coupler;

a plurality of array waveguides optically coupled between the first free space coupler and a second free space coupler, the plurality of waveguides having predetermined optical path length differences therebetween; and

a plurality of output waveguides optically coupled to the second free space coupler;

wherein the device further includes at least one additional waveguide optically coupled to the first free space coupler and disposed adjacent to a said input waveguide, said at least one additional waveguide being formed and arranged to substantially adiabatically transform an input optical signal which travels in said adjacent input waveguide towards the first free space coupler, in use of the device, from a single peak field to a multiple peak field for input to the first free space coupler.

The invention has the advantage of creating the multiple peak field shape, for example at least a double-peak field, necessary for passband flattening, but doing so substantially adiabatically i.e. without any significant excitation of higher order or radiation modes. Instead, the shape of the fundamental mode of the input waveguide is converted from a single peak to a multiple peak structure. For example, where a single additional waveguide is provided for the input waveguide, the (single-peak) fundamental mode of the input waveguide is converted to the double-peak fundamental mode of a twin waveguide system. Also, a further advantage is that this passband flattening operation is substantially wavelength insensitive.

Preferably, the or each said additional waveguide has a substantially tapered shape, being tapered so as to widen in width towards the first free space coupler along at least a substantial portion of its length. This is so that the transformation in mode shape occurs gradually and continuously. A single said additional waveguide may be provided for each input waveguide. In this case, each said additional waveguide and the respective adjacent input waveguide are both preferably directly connected to an input side of the first free space coupler. The additional waveguide is preferably of substantially equal width to the width of the respective adjacent input waveguide at the ends thereof which are connected to the first free space coupler. This means that the double-peak structure should be symmetrical. If these two waveguides were of different widths at the free space coupler,

the transmission spectrum of each output channel of the AWG would be asymmetrical which is usually highly undesirable.

In the preferred embodiments, each said additional waveguide has a half-tapered structure in which the angle of the taper is proportional to the difference in Neff (the effective refractive index) between the fundamental and first order system modes of the multiple waveguide system comprising a said input waveguide and each said additional waveguide provided therefor. This maximizes the efficiency of the mode shape transformer. Thus, any mode conversion which does occur is limited to an acceptable minimum level.

In the preferred embodiments each additional waveguide terminates in a free end at a predetermined, relatively short, distance away from the first free space coupler, for example a few millimeters away from an input edge of the coupler, the chosen length of each said additional waveguide being dependent on the spacing between the additional waveguide and the respective adjacent input waveguide.

Each additional waveguide may be generally straight, with its axis substantially parallel to the adjacent input waveguide. Alternatively, the additional waveguides may bend or be disposed at an angle to the adjacent input waveguide, for a portion of their length, while the end portion which is coupled to the first free space coupler is substantially parallel to said adjacent input waveguide.

Each input waveguide and each output waveguide may conveniently be single mode, or at least substantially single mode, waveguides. In this manner only the fundamental mode is excited in these waveguides. Nevertheless, in some embodiments a portion of the input waveguide which extends parallel to the additional waveguide (forming the mode shaping structure therewith) may be wider than a remaining potion of the input waveguide. For example, the input waveguide may be tapered so as to widen or narrow in width towards said different width portion.

In one embodiment a single said additional waveguide is provided for each input waveguide as described above. In another embodiment, two said additional waveguides are

provided for each input waveguide, one additional waveguide being disposed on each side of the first free space coupler. The three waveguides thus form a mode shaping structure which transforms the single peak input field in the input waveguide to a three-peak field. The three waveguides may all be connected to the input side of the first free space coupler, with all three waveguides preferably being parallel to one another. The three waveguides may be of substantially the same width at the first slab coupler. Alternatively, the middle waveguide may be of a different width to the other two. This will still produce a symmetrical passband. In an alternative embodiment, the input waveguide physically terminates short of the first free space coupler, but is optically coupled to this coupler via the two additional waveguides. This structure transforms the single peak input field in the input waveguide to a double-peak field.

In another possible embodiment, there is a single additional waveguide provided for at least one of the input waveguides, and the additional waveguide has a different width to the width of the respective adjacent input waveguide at the ends thereof which are connected to the first free space coupler, and a second additional waveguide, of substantially identical shape to the first additional waveguide, is optically coupled to the second free space coupler and disposed adjacent to a said output waveguide in an arrangement which is inverse to the arrangement of the first additional waveguide and its respective input waveguide. The second additional waveguide has substantially the same width at the second free space coupler as the width of the first additional waveguide at the first free space coupler, and the respective input and output waveguides adjacent to the first and second additional waveguides are of substantially equal widths at the first and second free space couplers respectively. In this manner, an asymmetric field is input to the first free space coupler, and an inversely asymmetric field is received at the output of the second free space coupler, the net effect being that the resulting AWG channel output is substantially symmetrical.

It will be appreciated that in the embodiments first described above, instead of placing the additional waveguide at the input side of the AWG, the additional waveguide could instead be placed at the output side, to achieve the same passband flattening effect in the AWG

device. Thus according to another aspect of the invention there is provided an arrayed waveguide grating (AWG) device comprising:

a plurality of array waveguides optically coupled between the first free space coupler and a second free space coupler, the plurality of array waveguides having predetermined optical path length differences therebetween;

and a plurality of output waveguides optically coupled to the second free space coupler; wherein

the device further includes at least one additional waveguide optically coupled to the second free space coupler and disposed adjacent to a said output waveguide, said at least one additional waveguide being formed and arranged to substantially adiabatically transform a multiple peak field, supported by said at least one additional waveguide together with said adjacent output waveguide, to a single peak field which travels in said adjacent output waveguide towards an output of the AWG device. In this embodiment the AWG need not necessarily include any input waveguides. Instead, the first free space coupler may be arranged at the edge of the device whereby an input optical fibre may be coupled directly thereto. Preferably, at least one additional waveguide is provided for each output waveguide.

According to another aspect of the invention there is provided an array waveguide grating (AWG) device comprising: at least one substantially single-mode first waveguide optically coupled to a first free space coupler; a plurality of array waveguides optically coupled between the first free space coupler and a second free space coupler, the plurality of array waveguides having predetermined optical path length differences therebetween; and a plurality of substantially single-mode second waveguides optically coupled to the second free space coupler; wherein the device further includes at least one additional waveguide optically coupled to one of the first and second free space couplers and disposed adjacent to a said first or second waveguide optically coupled to said one of the couplers, wherein said at least one additional waveguide is substantially tapered in width so as to widen towards the first free space coupler along at least a substantial portion of its length.

According to a further aspect of the invention there is provided an optical power splitter comprising an input waveguide and an additional waveguide disposed adjacent to said

input waveguide, said additional waveguide being formed and arranged to substantially adiabatically transform an input optical signal in said input waveguide from a single peak field at an input end of the splitter to a double peak field at an output end of the splitter. Such a device can also be used as an optical coupler, if used in the opposite signal direction. This splitter has the advantage of reduced asymmetry due to first order mode excitation, as compared with prior art splitters such as Y-branch splitters.

Preferred embodiments of the invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

DESCRIPTION OF THE DRAWINGS

Fig.1 is a schematic plan view of a conventional AWG;

Figs.2(a)to (c) illustrate in plan view three prior art passband flattening features which can be used in the AWG of Fig.1;

Fig.3 is a plan view of a new passband flattening feature, in the form of a mode shaper, for use in an improved AWG according to one embodiment of the invention;

Fig.4(a) is a graph plotting Loss of the fundamental system mode vs. Taper length, and also Extinction of the first order system mode vs. Taper length, for the mode shaper structure of Fig.3;

Fig.4(b) illustrates graphically the input and output mode fields for the mode shaper structure of Fig. 3 (when the AWG is being used as a demultiplexer), for a taper length L of 3-4mm;

Fig.5 is a plan view of a modified version of the feature of Fig.3;

Fig.6 is a graph of a specific waveguide taper shape used in the embodiment of fig.5;

Fig.7(a) is a plan view a modified version of the Fig.5 embodiment;

Fig.7(b) is a graph showing the flattened passband P_F obtained from an example fabricated AWG device including the passband flattening mode shaper structure of Fig.7(a), and also the generally Gaussian passband P_G obtained for a fabricated device based on the conventional Fig.1 design;

Fig.8 is a plan view of an alternative embodiment, using more additional waveguide;

Fig.9 is a plan view of another alternative embodiment of a passband flattening feature;

Fig.10 is a schematic plan view of another possible embodiment;

Fig.11 shows a modified version of the embodiment of Fig.7;

Fig. 12 is a plan schematic view of an optical splitter according to another embodiment of the invention; and

Fig.13 is a plan schematic view of a prior art Y-branch splitter.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig.3 shows an adiabatic mode shaper for flattening the passband of one channel of an AWG like that of Fig.1. Fig. 3 shows one input waveguide 20 of the AWG, coupled to an input face 21 of the first free space coupler 22 of the AWG. In this embodiment, the free space coupler is in the form of a slab coupler. One additional waveguide 24 is provided for the input waveguide 20 and is disposed adjacent and parallel thereto. The additional waveguide terminates a short distance L away from the slab coupler, and is tapered in width. The width of the additional waveguide at its free end 25 is less than the width of the input waveguide 20, and the waveguide tapers gradually so as to widen towards the slab coupler, its width W1 at the slab coupler being equal to the width of the input waveguide 20 at the slab coupler. This "twin waveguide" structure substantially adiabatically converts the fundamental mode I_S of a single waveguide to the fundamental system mode I_D of a pair of parallel waveguides of equal width. Convolution of this field with the fundamental mode of a single (output) waveguide 10 of the AWG results in a flattened spectral response (i.e. flattened passband) of the output channel. If there is more than one input waveguide 20 in the AWG, then each one is provided with one such additional waveguide 24.

The taper shape of the additional waveguide 24 in Fig.3 is parabolic. It was found that a parabolic taper is advantageous, resulting in low mode conversion (from fundamental to first order mode) and a relatively short length L. The graph in Fig.4(a) shows the extinction of the 1st order mode as a function of taper length L for two 6μm wide parallel guides, the lower tapered up from 2μm. The gap between the guides is 2μm, at the slab edge 21. A taper length L of 3-4mm is required to get below 30dB extinction. For this length, the input and output fields are as shown in Fig.4(b) which clearly shows the double-peak field (graph I_D) generated from the single-peak input field (graph I_S).

Another embodiment of the invention, uitlising a modified additional waveguide 20', is shown in Fig.5. In this case, only one side 30 of the additional waveguide is tapered, this

being the side closest to the adjacent input waveguide 20. Also, in this case the taper shape is no longer parabolic. The taper shape has been optimized to minimize the length L of the additional waveguide for a given acceptably low degree of mode conversion (to the first order mode). An additional benefit of this shorter taper shape is that the "blunt" (i.e. the non-zero width "point" 32 of the taper), which might tend to cause mode conversion (to higher order modes) is further removed from the evanescent tail of the incoming field in the input waveguide, thereby reducing any mode conversion effect.

To maximize the efficiency of the mode shape transformer (i.e. minimize the length for which it can be considered adiabatic), a taper shape can be designed in which the "taper angle" is proportional to the difference in effective refractive index between the fundamental and first-order system mode. This results in a taper shape defined by the following equations:

$$f(t) = a_1[(w_{out} - w_{in})t + w_{in}] + a_2[(w_{out} - w_{in})t + w_{in}]^2 + a_3[(w_{out} - w_{in})t + w_{in}]^3$$

$$z(t) = L\left[\frac{f(t) - f(0)}{f(1) - f(0)}\right]$$

$$y_{upper\_edge}(t) = (w_{out} - w_{in})t + w_{in} - \frac{w_{out}}{2}$$

$$y_{lower\_edge}(t) = -\frac{w_{out}}{2}$$

$$t = [0..1]$$

where f(t) is a third-order polynomial. The parameters a_1 to a_3 depend on the widths of the waveguides and the gap between them. The upper and lower edges of the taper are defined by the z(t) and y(t) coordinates. To determine the coefficients a_1 to a_3, the N_{eff} difference (ΔN_{eff}) between the 0^{th} and 1^{st} order modes is plotted is a function of the width of the tapered waveguide. This curve is then transformed to a "z-position(along taper) vs. width" curve, by integration of $1/\Delta N_{eff}$. The coefficients a_1 to a_3 represent a third order fit through this latter curve. The curve depends on the width of the tapered and non-tapered waveguide, the gap (g) between the waveguides (at the slab edge) and the type of taper shape chosen. In the Fig.5 embodiment we choose to keep the lower edge 31 of the tapered waveguide 20' constant. The result is the taper shape illustrated in the graph of Fig.6. For a mode shaper defined by w_{out}=6μm and gap=2μm, the optimum polynomial coefficients to

achieve the shortest length of the additional waveguide 20 for a given degree of mode conversion are given by:

a_1=275, a_2= -60 and a_3=20. We have found that this shape is significantly more efficient (namely, it results in a shorter taper) than the parabolic shape used in the Fig.3 embodiment. In general it is desirable for the mode shaper to be as short as possible in length in order to reduce fabrication sensitivity, reduce the AWG die size (area) and also reduce coupling between adjacent structures (other than the respective input waveguide) which would leave to crosstalk. The entire mode shaper has been designed to give significantly less than –30dB mode conversion to the first order mode.

We have carried out BPM simulations to determine optimum dimensions of the mode shaper for achieving optimum passband flattening. The passband is determined by the geometry of the "twin waveguide" structure at the slab edge, the geometry of the receiver waveguides at the output slab edge, and the output pitch (i.e. the spacing of the output waveguides 10). In our simulations we varied the associated parameters and compared the properties of the resulting simulated passbands with predetermined desired specifications, in order to arrive at the optimum parameter values. Accordingly, we found that the optimum conditions, for output waveguides of 6μm width and output waveguide pitch equal to 21μm, are to have the width w_{out} of both waveguides equal to 4.5μm at the slab edge, with a gap, g, of 3.5μm between them. Thus, we have designed the embodiment shown in Fig. 7(a) in which an additional linear taper section 25,26 has been added at the end of each of the input waveguide 20 and the additional waveguide 24, where they are coupled to the slab coupler, so as to reduce the width of each waveguide from the width W1 of the input waveguide (in this embodiment W1=6μm) to the desired smaller end width W2=4.5μm. This linearly tapered section can be relatively short, because it is symmetrical and therefore coupling to (i.e. excitation of) the first order mode is zero. (Where a waveguiding structure is asymmetrical this encourages excitation of the first order mode. If the structure is lengthened this reduces excitation of the first order mode.) For the above-quoted optimum dimensions we have used a linear taper length of 800μm with the length L of the remaining portion of the additional waveguide 20' equal to 4000μm (tapering to a width of w_{in}=1μm at the free end of the additional waveguide). Fig.7(b) is a graph comparing the flattened passband P_F obtained from an example device

which we have fabricated incorporating the passband flattening mode shaper structure of Fig.7(a), and the generally Gaussian passband P_G obtained for a fabricated device based on the conventional Fig.1 design (i.e. without the mode shaper of the invention). The passbands are here plotted as Transmission (dB) vs. Relative Wavelength (nm) (i.e. wavelength relative to the central wavelength of the channel whose passband is shown).

In principle, passband flattening could also be achieved using more than one additional short waveguide 24 like that in Figs. 3 or 7. For example, Fig.8 shows an embodiment in which a pair of additional waveguides 30,32 are adjacent each input waveguide 20, one on either side of the input waveguide. This structure substantially adiabatically transforms the (single-peak) fundamental mode of the input waveguide 20 to a three-peak fundamental system mode of the three waveguide structure. Convolution of this three-peak field with the fundamental mode of an output waveguide of the AWG again results in a flattened passband shape. The taper shape of the lower additional waveguide 30 is the same as that of the additional waveguide 24 in Fig.7(a). The shape of the upper additional waveguide 32 mirrors the shape of the lower one 30. Additional linearly tapered waveguide end portions 25,36,37 are provided on all three waveguides, similarly to in the Fig.7(a) design, to convert the final geometry of the three waveguide (at the slab) to an optimum geometry (again calculated using BPM simulations) for passband flattening.

In any of the above-described embodiments the output waveguides may be single mode waveguides 10 connected directly to the output face 40 of the second slab coupler 4. Alternatively, the ends of the output waveguides which are coupled to the slab coupler may be tapered (preferably adiabatically linearly tapered) so as to widen towards the second slab coupler. This has been found to have the benefit of reducing "ripple" which may be present in the flattened top of the output channel passband.

Of course it will be readily appreciated that instead of using the adiabatic mode shaping structure at the input side of the AWG it could be used at the output side. For example, one of the described additional (tapered) waveguides 24 could be provided for each output waveguide 10, each additional waveguide being coupled to the output face 40 of the second slab coupler 4 and disposed adjacent the respective output waveguide in a similar

manner as shown in Fig.5 for the input waveguide. Each output waveguide and its respective additional waveguide (forming one "adiabatic mode shaper") will together support a double peak signal which is adiabatically converted to a single peak signal carried by the output waveguide 10 all the way to the edge 12 of the die for output therefrom. The convolution of the single peak (fundamental mode) filed from the input waveguide 2 and the double peak field supported by the mode shaper produces the desired flattened passband. Each mode shaper may be identical. Alternatively, in some embodiments it may be desirable for the widths of the mode shaper waveguides (and the output waveguides), where they are coupled to the second slab 4, to be slightly different from one mode shaper to the next. For example, where it is desired to increase the uniformity in the adjacent channel crosstalk, the passband (shape) uniformity, or another performance parameter of the AWG device, as described in our earlier British patent application no.0106014.4 (in which we "chirp" the widths of the output waveguides at the output slab coupler). Thus, the widths of the waveguides in each mode shaper may increase by a predetermined amount from one mode shaper to the next, for example from channel 1 to channel 40 in a 40 channel AWG, where channel 1 is the lowest frequency channel (although the widths of each waveguide in any one mode shaper would still be substantially identical, at the slab coupler 4).

It will be understood that the triple-waveguide mode shaper structure of Fig.8 could be used for each output waveguide, rather than the double waveguide mode shaper as above-described, although the larger die space required may make this a less attractive option.

Where mode shapers are provided at the output side of the device, as above-described, embodiments are possible where no input waveguides are provided in the device. Instead, the first free space coupler may be arranged at the input edge of the die 1 whereby an input optical fibre may be coupled directly thereto. The convolution of the double-peak field produced by the mode shapers at the output side of the device, with the fundamental mode of the output optical fibres which would be coupled to the edge 12 of the die 1 to receive the output channel signals from the output waveguides 10, produces the required flattened passband.

Fig. 9 shows a modified version of the three waveguide embodiment of Fig.8. In this case, the two additional waveguides 30,32 are physically connected to the first slab coupler, but the input waveguide 20 terminates a short distance away from the slab coupler, before reaching the coupler. The free end 26 of the input waveguide tapers to a point, this tapered end being effectively sandwiched between the two additional waveguides 30,32. This ensures good (adiabatic) coupling of the input signal from the input waveguide 20 to the two additional waveguides 30,32. In this design the (single-peak) fundamental mode I_S of the input waveguide is adiabatically converted to a double-peak fundamental system mode I_D of the two additional waveguides 30,32. Convolution of this double-peak field with the fundamental mode of an output waveguide of the AWG creates a flattened spectral response in the AWG output channels.

Another possible embodiment is illustrated in Fig. 10. This illustrates schematically the use of a complementary mode shaper structure at both the input and output sides of the AWG (only the input face 21 of the first slab 3 and the output face 40 of the second slab 4 are shown, the array waveguides not being shown). In this case, the widths of the two waveguides in each mode shaper are different where they are coupled to the input/output slab 3,4, but the respective input and output waveguides 2,10 each have the same width W3 and the additional waveguides 52,54 each have the same width W4 (at the slabs) (W3≠W4). The structure of the output mode shaper 60 is the inverse to that of the input mode shaper 50. Thus, the shape of the additional waveguides 52,54 is identical, but the orientation of the output additional waveguide 54 is inverse to that of the input additional waveguide 52, as shown in Fig.10, and also the output additional waveguide is disposed above the output waveguide 10 while the input additional waveguide 52 is disposed below the input waveguide 2. The gap g between the waveguides in each mode shaper, at the respective slab, is the same on each side of the AWG. With this inverse mode shaper pairing, an asymmetric double-peak field is formed by the input mode shaper 50 and an inversely asymmetric double-peak field if formed by the output mode shaper 60. The convolution of these two fields (effected by the arrayed waveguide grating) results in a substantially symmetric flattened passband. As a further improvement, inverse bending of the input and output waveguides 2,10 in the fan-in and fan-out regions of the AWG, as described in our earlier British Patent Application No.0106013.6 the content of which is

incorporated herein by reference, may be used to further ensure that the final flattened passband is symmetrical (or at least substantially symmetrical).

The mode shapers in the Fig.10 embodiment may be based on any of the mode shaper structures of Figs. 3,5 and 7. It will be generally understood that this concept of using inversely shaped mode shapers at the input and output sides of the AWG can also be extended to the use of triple waveguide (or other multi waveguide) mode shapers as illustrated in Figs.8 and 9.

In all of the above-described embodiments, where reference is made to input waveguides and output waveguides, it will be appreciated that these terms are used in relation to when the AWG is used as a demultiplexer. However, it will be understood that the same AWG could equally well be used as a multiplexer, in which case the terms input and output would be interchanged, as optical signals are then travelling through the AWG in the opposite direction. For the avoidance of doubt it will thus be understood that the wording "input" and "output" is not intended to be limiting, the attached claims being intended to cover an AWG which is used as a demultiplexer or as a multiplexer.

It will be appreciated that further modifications and variations are possible without departing from the scope of the invention. For example, it is expressly intended that all combinations of those elements which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. One possible modification, for example, could be that the or each of the additional waveguides 24,30,32, 52,54 used in the above-described designs may terminate just before the input/output face of the respective slab coupler (to which it is optically coupled), rather than being physically connected thereto. As long as the gap between the slab and the end(s) of the additional waveguides is small (a few μm) the divergence and associated loss would be limited.

Additionally, other taper shapes than those above-described for the additional waveguides are possible, although a longer length of mode shaper than that in the Fig.7 embodiment may then be required in order that the transformation of the single peak field to the double

peak field occurs substantially adiabatically i.e. with preferably less than –30dB mode conversion from the 0^{th} to the 1^{st} order (guided) modes.

In another possible modification, the additional waveguides may extend further from the respective slab coupler to which it is optically coupled than as illustrated in the Figures. In principle, they could extend all the way back to the input/output edge of the AWG die, although we do not believe this to be the best mode of the invention since problems and complications are likely to occur associated with any bending of the input/output waveguides in the AWG design.

Also, modified versions of the above-described embodiments are possible in which the input/output waveguide may be tapered immediately before the mode shaper structure, such that the portion of the input/output waveguide which forms one waveguide of the mode shaper is of greater or smaller width than the remaining length of the input/output waveguide. This is illustrated in Fig.11 which shows a mode shaper structure like that of Fig.7, coupled to the input face 21 of the first slab coupler 3, and having a linearly (adiabatically) tapered portion 62 which widens towards the mode shaper, such that the width W_{out} of the portion of the input waveguide 20 which forms part of the mode shaper structure is greater than the width W_s of the initial portion 63 of the input waveguide (which is coupled to the mode shaper via the tapered input waveguide portion 62).

It is worth noting that where there is more than one input waveguide, it is advantageous for every input waveguide to have a substantially identical passband flattening feature (PBF) 30 (i.e. mode shaper structure), whereby each PBF feature is flanked on one or both sides by at least one identical PBF feature. We believe this will reduce radiation effects (the neighbours modify the radiation mode spectrum). Thus it can also be advantageous to put an extra mode shaper structure, consisting of a dummy input waveguide portion and respective additional waveguide(s), on each side of the input waveguide array, where there is no input waveguide, just so every PBF feature is flanked on both sides by an identical PBF feature.

It will further be appreciated that the adiabatic mode shaper shown in Fig.3, or the adiabatic mode shaper shown in Fig.5, can be used in any application where it may be desirable to transform adiabatically a single peak mode field to a double peak mode field. For example, a 1 x 2 optical power splitter can be formed using such a structure. Fig.12 illustrates a novel splitter, in which a tapered waveguide 72 is disposed adjacent to a single-mode (or at least substantially single-mode) input waveguide 70. Similarly to the Fig.5 embodiment, the tapered waveguide 72 commences at a first position X1 (along the X-axis in Fig.12) at an input end of the splitter and tapers in width along its length, so as to widen from a starting width W_{in}, which is less than the width of the input waveguide 70, to a final width at the output end X2 of the splitter which is equal to the width W_{out} of the input waveguide. The taper shape of the tapered waveguide 72 is designed in the same manner as already described above with reference to the embodiment of Fig.5. Alternatively a parabolic taper shape like that in the Fig.3 embodiment could be used. In either case the taper shape is thus such that a single mode field F1 in the input waveguide 70 at the input end of the splitter is transformed substantially adiabatically (i.e. preferably less than –30dB mode conversion from 0^{th} to 1^{st} order guided modes) to a double-peak mode field F2 at the output end of the splitter.

Such a splitter has significant advantages over conventional splitters such as a Y-branch splitter as shown in Fig.13. Power splitters are extremely sensitive to power present in the 1^{st} order mode in either the common input or the split output section of the basic 1×2 splitter. Power in the 1^{st} order mode leads to asymmetry in the splitter. Splitter asymmetry generally results in a wavelength and polarization dependent response and can negatively impact a number of performance parameters. The most important parameters are IL, ILU, WDL and PDL. It can be shown that the $1^{st}/0^{th}$ order mode power ratio ideally needs to be suppressed to below -45dB to reduce asymmetry of a single splitter stage to below 0.1dB. Given the fact that splitter specifications often now do not allow for more than ~0.3dB total asymmetry, and that a typical splitter consists of multiple stages, it can be appreciated that suppression of the 1^{st} order mode to reduce asymmetry is a key issue in the design of a splitter. The splitter design of Fig.12, based on the adiabatic mode shaper, reduces the $1^{st}/0^{th}$ order mode power ratio in an individual 1×2 splitter and hence improves the aforementioned performance parameters. As illustrated in Fig.12, the adiabatic mode-

shaping splitter adiabatically transforms the 0^{th} order mode on the input waveguide (which is fully localized in the lower waveguide 70 in Fig.12) to the 0^{th} order mode on the splitter output (which is distributed equally between the two branches 70,72 of the splitter).

Splitter asymmetry is generally caused by two factors: (1) fiber-chip misalignment at the input edge of the optical chip or die in which the splitter is incorporated: this can cause radiation generation; and (2) 1^{st} order mode excitation due to radiation recapturing i.e. capture of radiation generated by fiber-chip misalignment or from other sources in surrounding areas of the chip. The key advantage of the adiabatic mode shaper of Fig.12 as a splitter is that asymmetry can only be caused by power collected into the "loose" input 73 (at position X1) of the tapered waveguide 72. By routing this input away from areas where "noise" radiation can be coupled in, and making the mode shaping section substantially adiabatic, excitation of the 1^{st} order mode can be successfully suppressed. As an additional advantage, the proposed structure does not contain any discontinuities, unlike in conventional splitters such as Y-branch or MMI (Multi-mode Interferometer) splitters. For example, in a Y-branch splitter like that of Fig. 13 there is discontinuity at the junction between the input waveguide 80 and the start of the branching region 82, and also in practice at the tip 85 of the V-shape formed between the two output waveguides 83,84 where a straight edge or "blunt" is usually formed (due to manufacturing tolerances making it difficult in practice to fabricate a perfect point or V-shape). Such discontinuities lead to radiation losses which consequently increase the insertion loss of the splitter.

It will be readily appreciated that the 1 x 2 splitter of Fig.12 can be modified to form a 1 x 3 splitter by placing a second tapered waveguide on the other side of the input waveguide 70 to the first tapered waveguide 72, similarly to the arrangement shown in Fig. 8. Moreover, the splitter can be used in the opposite direction to that described above, in order to act as a coupler. Thus use of the terms "input" and "output" above and in the claims is not intended to limit the scope of the invention to the use of the device in one direction only.

CLAIMS

1. An array waveguide grating (AWG) device comprising:

at least one input waveguide optically coupled to a first free space coupler;

a plurality of array waveguides optically coupled between the first free space coupler and a second free space coupler, the plurality of waveguides having predetermined optical path length differences therebetween; and

a plurality of output waveguides optically coupled to the second free space coupler;

wherein the device further includes at least one additional waveguide optically coupled to the first free space coupler and disposed adjacent to a said input waveguide, said at least one additional waveguide being formed and arranged to substantially adiabatically transform an input optical signal which travels in said adjacent input waveguide towards the first free space coupler, in use of the device, from a single peak field to a multiple peak field for input to the first free space coupler.

2. An AWG device according to claim 1, wherein each said additional waveguide is substantially tapered so as to widen in width towards the first free space coupler along at least a substantial portion of the length of the additional waveguide.

3. An AWG device according to any preceding claim, wherein each said additional waveguide comprises a half-tapered structure in which the angle of the taper is proportional to the difference in the effective refractive index, Neff, between the fundamental and first order system modes of the multiple waveguide system consisting of the said input waveguide and each respective said additional waveguide disposed adjacent thereto.

4. An AWG device according to claim 3, wherein each said additional waveguide comprises a taper shape defined by the following equations:

$$f(t) = a_1\left[(w_{out} - w_{in})t + w_{in}\right] + a_2\left[(w_{out} - w_{in})t + w_{in}\right]^2 + a_3\left[(w_{out} - w_{in})t + w_{in}\right]^3$$

$$z(t) = L\left[\frac{f(t) - f(0)}{f(1) - f(0)}\right]$$

$$y_{upper\_edge}(t) = (w_{out} - w_{in})t + w_{in} - \frac{w_{out}}{2}$$

$$y_{lower\_edge}(t) = -\frac{w_{out}}{2}$$

$$t = [0..1]$$

where f(t) is a third-order polynomial, and the upper and lower edges of the taper are defined by the z(t) and y(t) coordinates.

5. An AWG device according to claim 1 or claim 2, wherein each said additional waveguide is substantially parabolically tapered along at least a portion of its length.

6. An AWG device according to any preceding claim, wherein each additional waveguide terminates in a free end at a predetermined distance away from the first free space coupler.

7. An AWG device according to any preceding claim, wherein each additional waveguide is substantially straight with its axis substantially parallel to the adjacent input waveguide.

8. An AWG device according to any of claims 1 to 6, wherein an end portion of each additional waveguide which is coupled to the first free space coupler is substantially parallel to said adjacent input waveguide, and a further portion of the additional waveguide is disposed at an angle to the adjacent input waveguide.

9. An AWG device according to any preceding claim, wherein a single said additional waveguide is provided for each input waveguide.

10. An AWG according to claim 9, wherein each additional waveguide and each input waveguide are all directly connected to an input side of the first free space coupler.

11. An AWG according to claim 10, wherein each additional waveguide is of substantially equal width to the width of the respective adjacent input waveguide where they are connected to the first free space coupler.

12. An AWG device according to claim 10, wherein a single additional waveguide is provided for at least one input waveguide and the additional waveguide has a different width to the width of the respective adjacent input waveguide at respective ends thereof which are connected to the first free space coupler, and a second additional waveguide of substantially identical shape to the first additional waveguide, is provided for at least one of the output waveguides, the second additional waveguide being optically coupled to the second free space coupler and disposed adjacent to the respective output waveguide in an arrangement which is inverse to the arrangement of the first additional waveguide and its respective input waveguide, and the second additional waveguide has substantially the same width at the second free space coupler as the width of the first additional waveguide at the first free space coupler, and the respective said input and output waveguides adjacent thereto are of substantially equal widths at the first and second free space couplers respectively.

13. An AWG device according to any of claims 1 to 8, wherein two said additional waveguides are provided for each input waveguide, one additional waveguide being disposed on either side of the respective input waveguide.

14 An AWG according to claim 13, wherein the two additional waveguides and the respective input waveguide together form a mode shaping structure for transforming the single peak mode field in the input waveguide to a three-peak mode field for input to the first free space coupler.

15. An AWG according to claim 14, wherein the input waveguide physically terminates short of the first free space coupler, but is optically coupled to this coupler via the two additional waveguides, whereby the two additional waveguides and the respective adjacent input waveguide together form a mode shaping structure transforming the single peak

mode field in the input waveguide to a double-peak mode field for input to the first free space coupler.

16. An AWG device according to any preceding claim, wherein the length of said at least one additional waveguide is dependent upon the spacing between said at least one additional waveguide and said adjacent input waveguide.

17. An AWG device according to any preceding claim, wherein said at least one additional waveguide is formed and arranged such that the transformation of the single peak field to the multiple peak field produces less than –30dB mode conversion from the fundamental to the first order mode.

18. An arrayed waveguide grating (AWG) device comprising:
a plurality of array waveguides optically coupled between a first free space coupler and a second free space coupler, the plurality of array waveguides having predetermined optical path length differences therebetween;
and a plurality of output waveguides optically coupled to the second free space coupler; wherein
the device further includes at least one additional waveguide optically coupled to the second free space coupler and disposed adjacent to a said output waveguide, said at least one additional waveguide being formed and arranged to substantially adiabatically transform a multiple peak field, supported by said at least one additional waveguide together with said adjacent output waveguide, to a single peak field which travels in said adjacent output waveguide towards an output of the AWG device.

19. An array waveguide grating (AWG) device comprising:
at least one substantially single-mode first waveguide optically coupled to a first free space coupler;
a plurality of array waveguides optically coupled between the first free space coupler and a second free space coupler, the plurality of array waveguides having predetermined optical path length differences therebetween; and

a plurality of substantially single-mode second waveguides optically coupled to the second free space coupler; wherein the device further includes at least one additional waveguide optically coupled to the first free space coupler and disposed adjacent to a said input waveguide, said at least one additional waveguide being substantially tapered in width so as to widen towards the first free space coupler along at least a substantial portion of its length.

20. A multiplexer incorporating an AWG device according to any preceding claim.

21. A demultiplexer incorporating an AWG device according to any preceding claim.

22. A communications system incorporating at least one AWG device according to any of claims 1 to 19.

23. An AWG device substantially as described herein and with reference to Figs. 1 and 3.

24. An AWG device substantially as described herein and with reference to Figs. 1 and 5.

25. An AWG device substantially as described herein and with reference to Figs. 1 and 7.

26. An AWG device substantially as described herein and with reference to Figs. 1 and 8.

27. An AWG device substantially as described herein and with reference to Figs. 1 and 9.

28. An AWG device substantially as described herein and with reference to Figs. 1 and 10.

29. An optical power splitter comprising an input waveguide and an additional waveguide disposed adjacent to said input waveguide, said additional waveguide being formed and arranged to substantially adiabatically transform an input optical signal in said input waveguide from a single peak field at an input end of the splitter to a double peak field at an output end of the splitter.

30. A splitter according to claim 29, wherein said additional waveguide comprises a tapered portion along the length of which the width of the additional waveguide widens towards the output end of the splitter.

31. A splitter according to claim 29 or claim 30, wherein said additional waveguide comprises a half-tapered structure in which the angle of the taper is proportional to the difference in the effective refractive index, Neff, between the fundamental and first order system modes of the multiple waveguide system consisting of the said input waveguide and said additional waveguide disposed adjacent thereto.

32. A splitter according to claim 31, wherein said additional waveguide comprises a taper shape defined by the following equations:

$$f(t) = a_1\left[(w_{out} - w_{in})t + w_{in}\right] + a_2\left[(w_{out} - w_{in})t + w_{in}\right]^2 + a_3\left[(w_{out} - w_{in})t + w_{in}\right]^3$$

$$z(t) = L\left[\frac{f(t) - f(0)}{f(1) - f(0)}\right]$$

$$y_{upper\_edge}(t) = (w_{out} - w_{in})t + w_{in} - \frac{w_{out}}{2}$$

$$y_{lower\_edge}(t) = -\frac{w_{out}}{2}$$

$$t = [0..1]$$

where f(t) is a third-order polynomial, and the upper and lower edges of the taper are defined by the z(t) and y(t) coordinates.

33. A splitter according to claim 29 or claim 30, wherein said additional waveguide is substantially parabolically tapered along at least a portion of its length.

34. A splitter according to any of claims 29 to 33, wherein said additional waveguide terminates in a free end at an input end of the splitter.

35. A splitter according to any of claims 29 to 34, wherein said additional waveguide is substantially straight with its axis substantially parallel to the adjacent input waveguide.

36. A splitter according to any of claims 29 to 35, wherein a further additional waveguide is provided adjacent the input waveguide, on an opposite side of the input waveguide to the first additional waveguide, said additional waveguides being formed and arranged to substantially adiabatically transform an input optical signal in said input waveguide from a single peak field at an input end of the splitter to a three- peak field at an output end of the splitter.

37. A splitter according to any of claims 29 to 36, wherein at an output end of the splitter the or each said additional waveguide is of substantially equal width to the width of the adjacent input waveguide.

38. A splitter substantially as described herein and with reference to Fig.12.

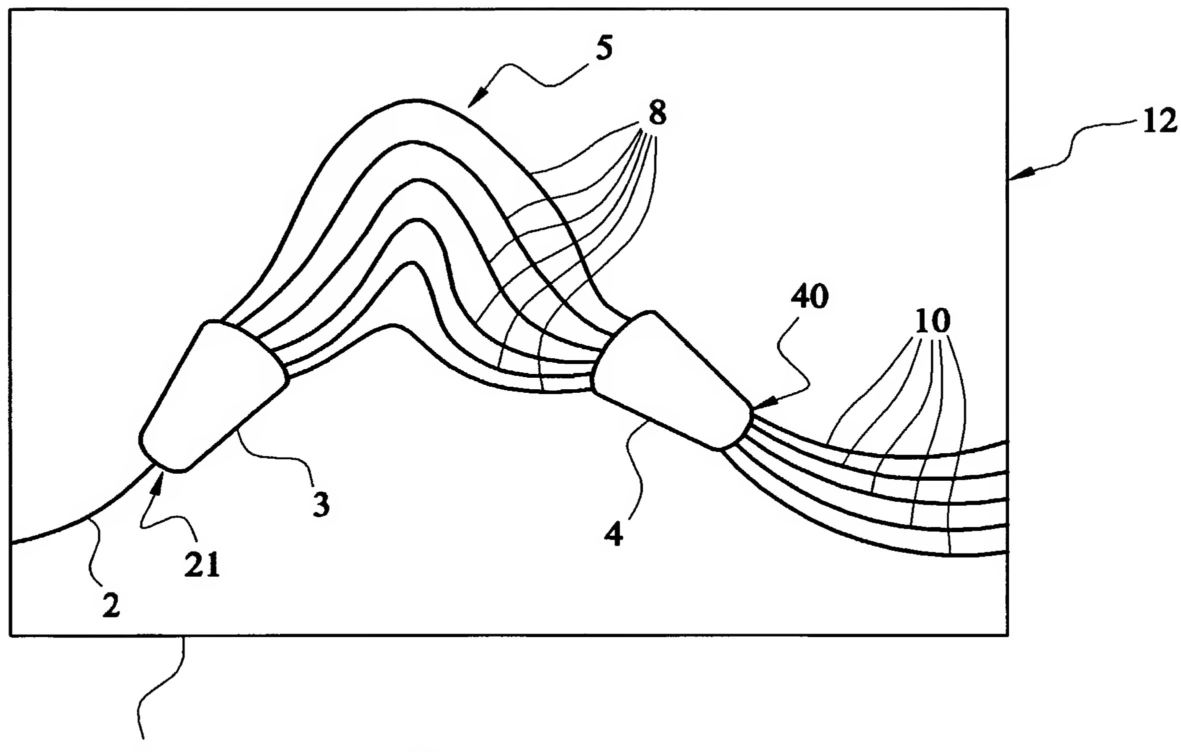

FIG. 1

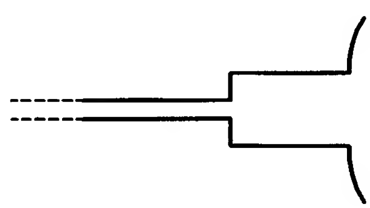

FIG. 2(a)

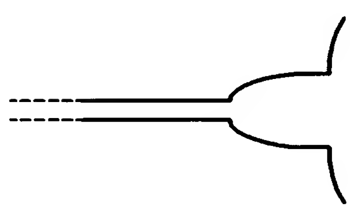

FIG. 2(b)

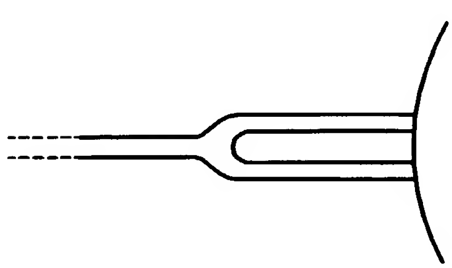

FIG. 2(c)

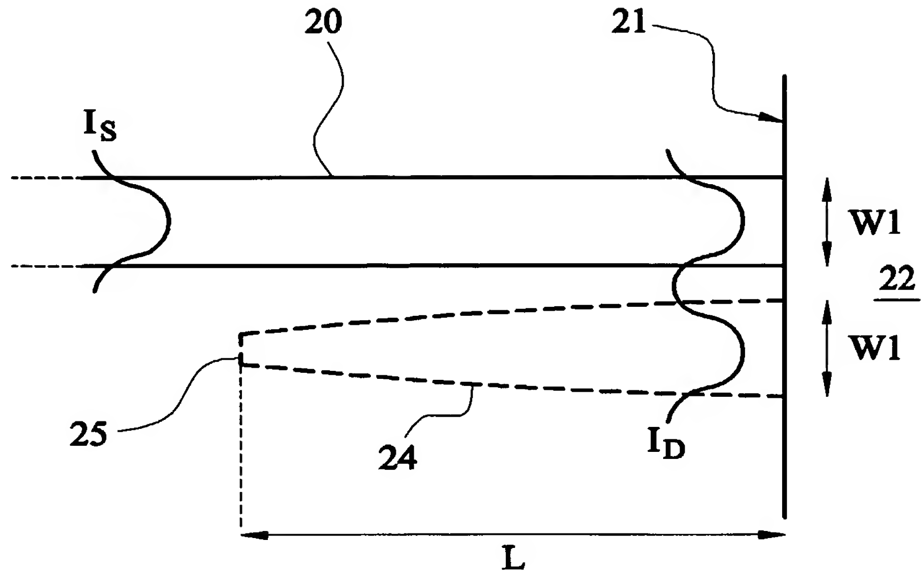
20
21
I_S
W1
22
W1
25
24
I_D
L

FIG. 3

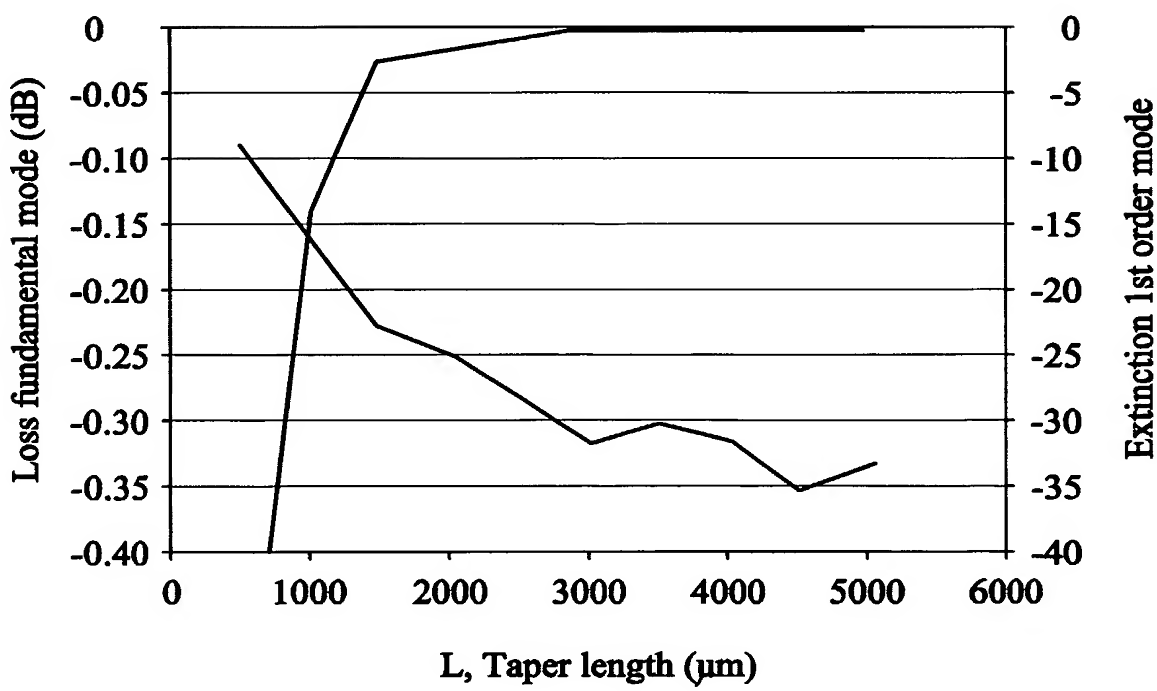
0
-0.05
-0.10
-0.15
-0.20
-0.25
-0.30
-0.35
-0.40
Loss fundamental mode (dB)
0
-5
-10
-15
-20
-25
-30
-35
-40
Extinction 1st order mode
0
1000
2000
3000
4000
5000
6000
L, Taper length (μm)

FIG. 4(a)

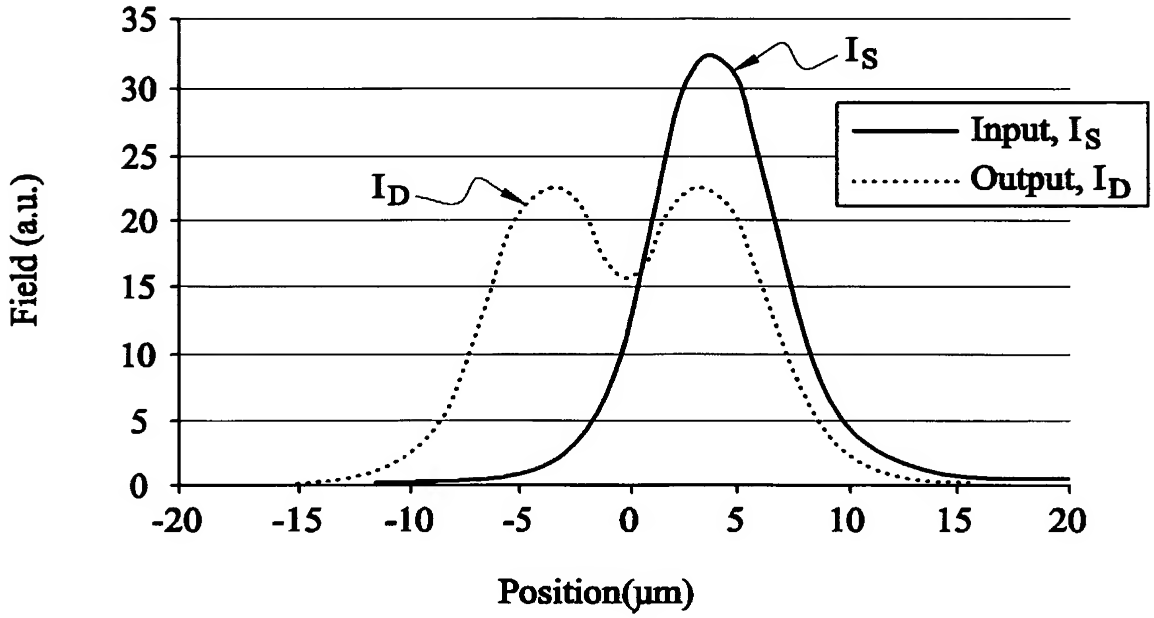
35
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
Field (a.u.)
Position(μm)
I_S
I_D
Input, I_S
Output, I_D

FIG. 4(b)

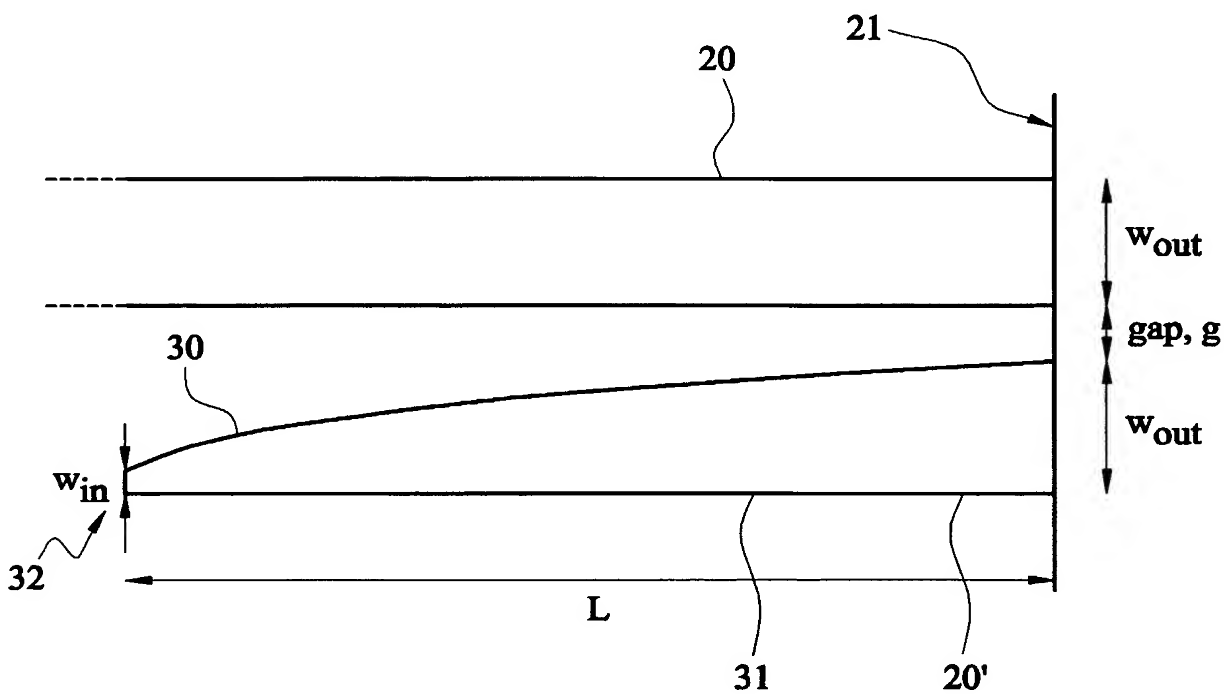
21
20
w_{out}
gap, g
w_{out}
30
w_{in}
32
L
31
20'

FIG. 5

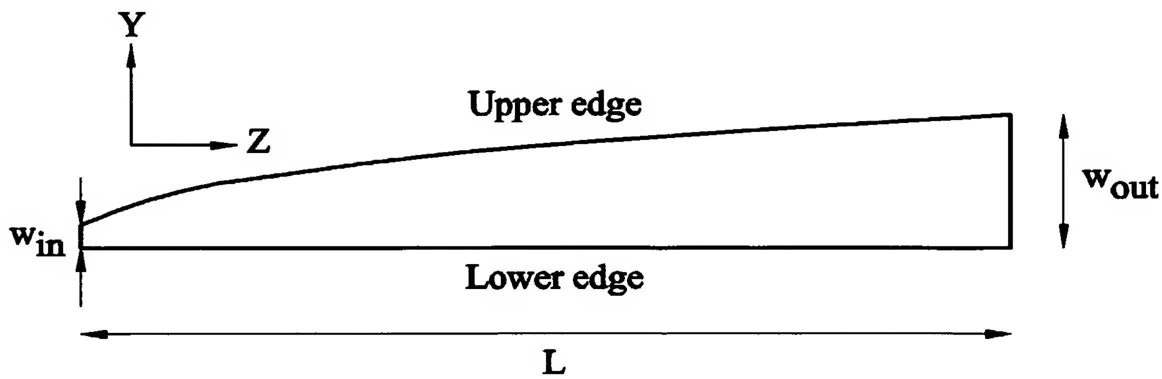
Y
Z
Upper edge
w_{out}
w_{in}
Lower edge
L

FIG. 6

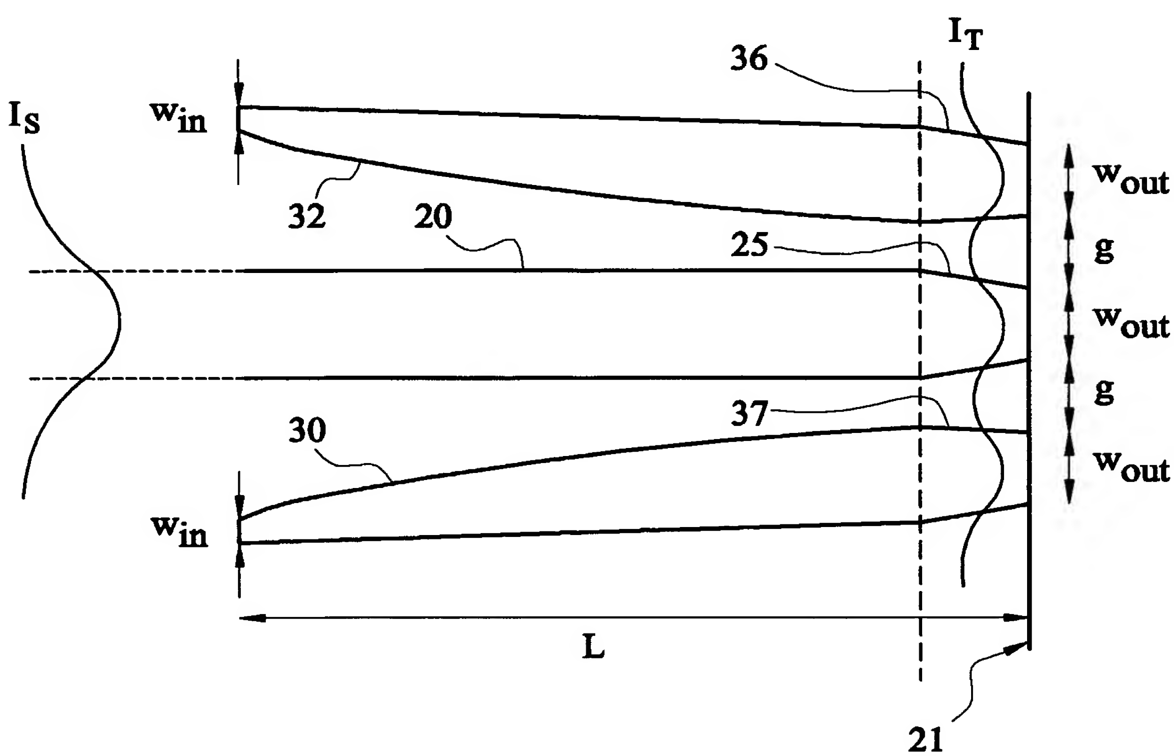
I_T
36
I_S
w_{in}
w_{out}
32
20
25
g
w_{out}
g
37
30
w_{out}
w_{in}
L
21

FIG. 8

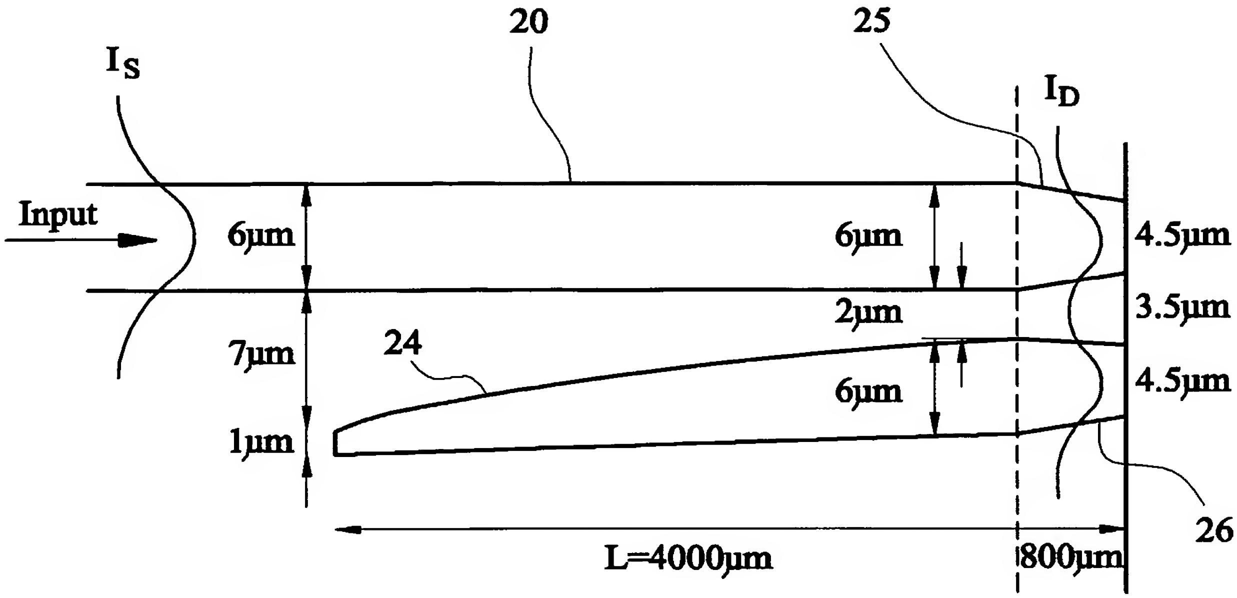
20
25
I_S
I_D
Input
6μm
6μm
4.5μm
2μm
3.5μm
7μm
24
6μm
4.5μm
1μm
26
L=4000μm
800μm

FIG. 7(a)

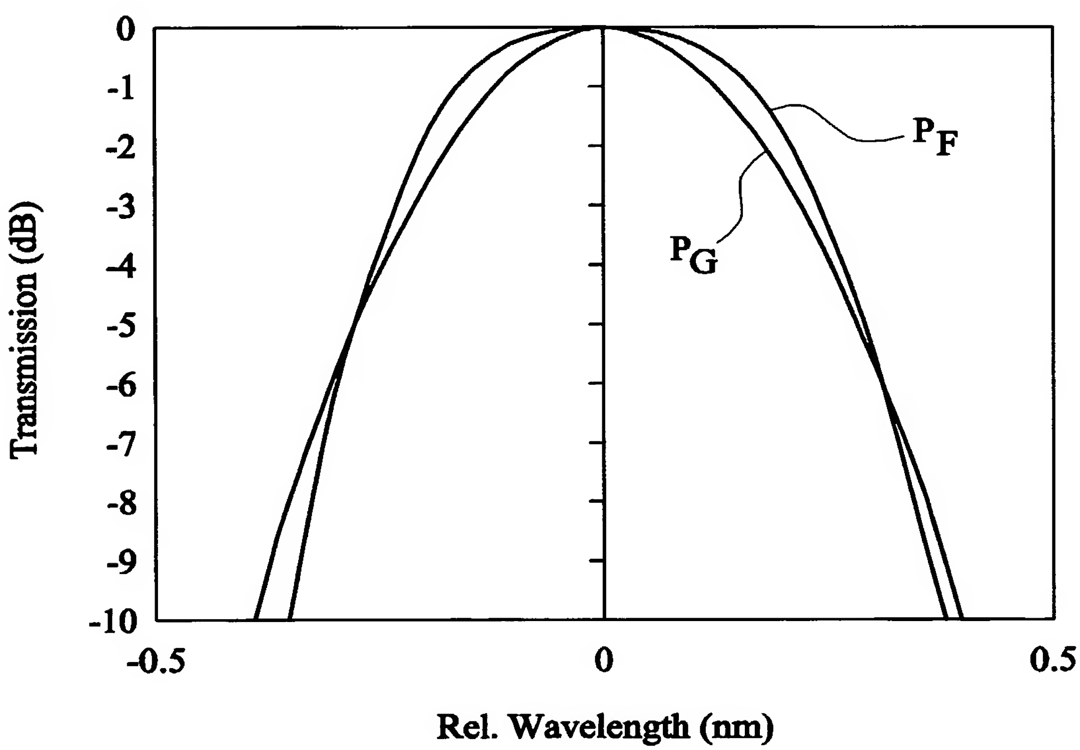
0
-1
-2
-3
-4
-5
-6
-7
-8
-9
-10
Transmission (dB)
P_F
P_G
-0.5
0
0.5
Rel. Wavelength (nm)

FIG. 7(b)

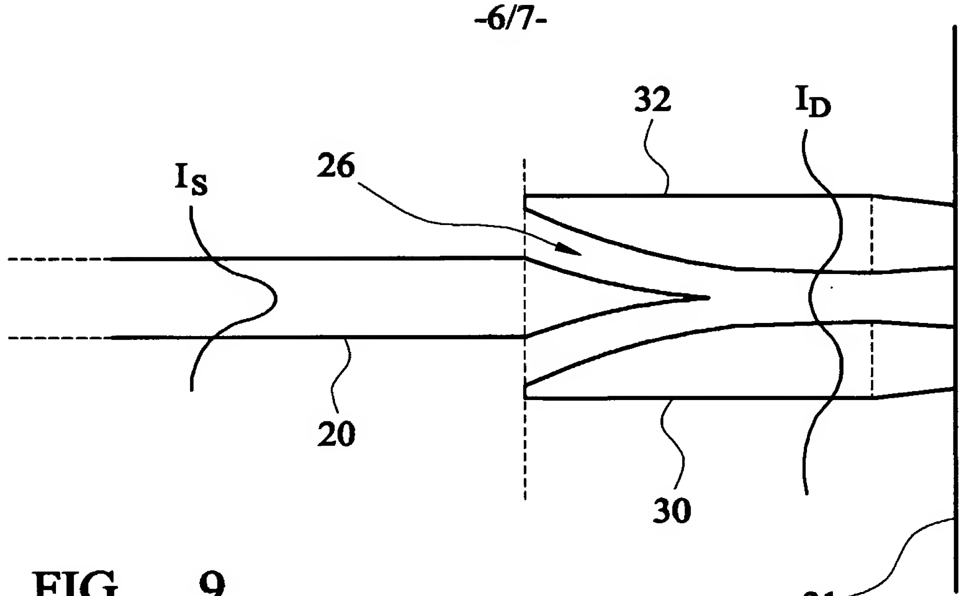

FIG. 9

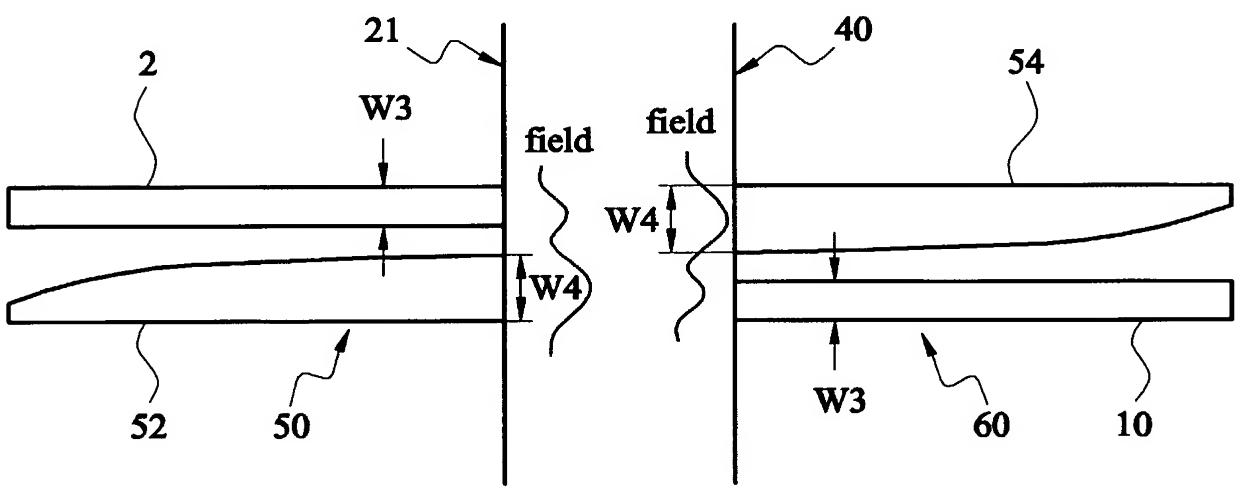

FIG. 10

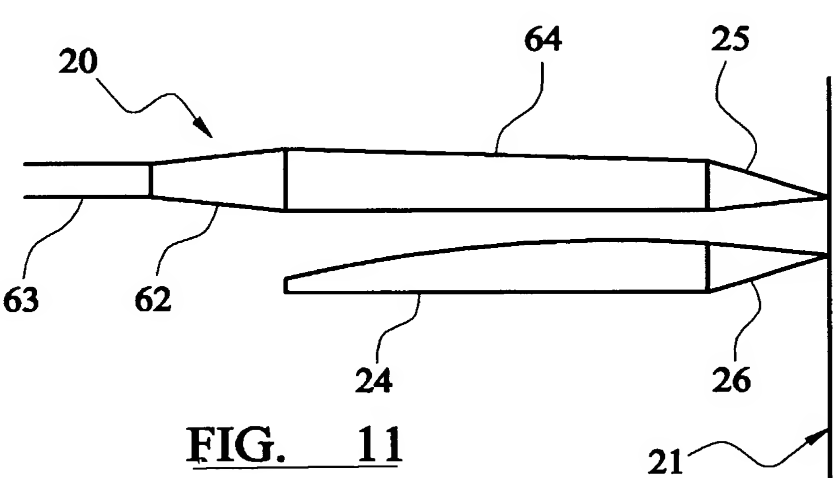

FIG. 11

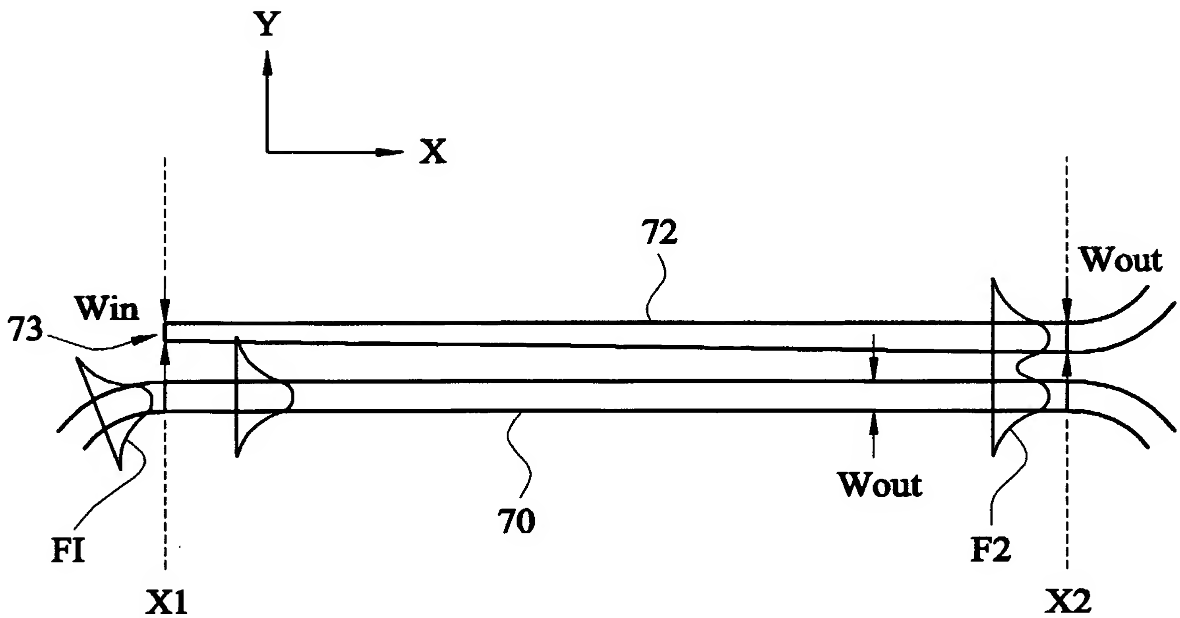

FIG. 12

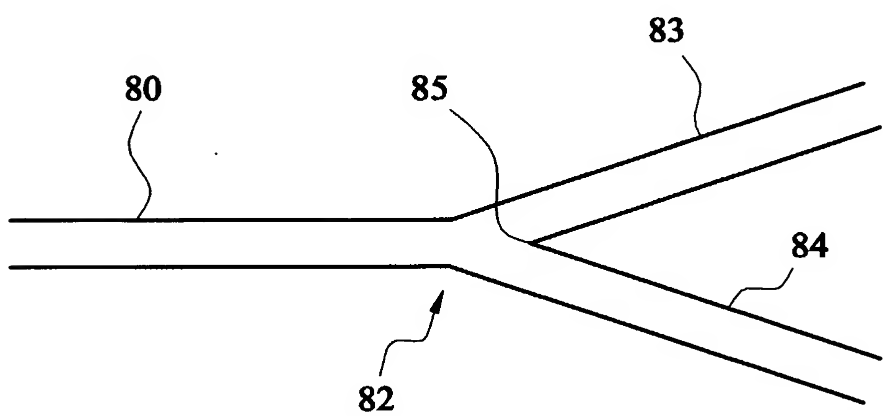

FIG. 13

PRIOR ART